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Distributed Locating Algorithm MDS-MAP (LF) Based on Low-Frequency Signal

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Abstract. The positioning error of distributed MDS-MAP algorithms comes from two aspects: the local positioning error and the position fusion error. In an attempt to improve the positioning result in both local positioning accuracy and global convergence probability, this paper proposes a novel MDS-MAP(LF) algorithm, which uses low frequency signal to measure the inter-sensor distance rather than shortest path algorithms. The proposed MDS-MAP(LF) algorithm leverages the propagation feature of low frequency signal to acquire a more precisely two-hop distance. The simulation and analysis results indicate that the accuracy of local positioning is improved by more than 3%. With the use of cluster expansion, MDS-MAP(LF) also shows a better convergence with comparison to the former classical distributed MDS-MAP algorithm.

Keywords: Wireless Sensor Network, Multi-dimensional Scaling, Low-frequency Signal, Localization.

1. Introduction

Wireless sensor network has become mature in recent years, a surging number of industries begin to use wireless sensor nodes to enrich the network data. With the popularity of this technology, users are no longer satisfied with simple data acquisition, but further application of data, such as data mining and cloud computing technologies. These in-depth data applications gradually make the node localization becomes an essential technology in many situations, since in some application scenarios, such as a forest fire control system, captured data will be meaningless once the sensor nodes localization failed. However, sensor nodes are typically resource constrained which contradicts the requirement of accurate localization functions. This makes the traditional position acquisition method, such as GPS positioning, difficult to be realized. Sensor nodes are often distributed randomly and the scale is relatively large [1], therefore, the realization of a stable and scalable localization method is urgently demanded. Nowadays, wireless sensor network, which has realized many key technologies on network construction and communication, shows a hot research area of efficient positioning.

The positioning function of wireless sensor network is inspired by the satellite positioning system. However, it is impossible to implement a GPS chip on every wireless sensor node because of the huge cost of the hardware. With the impetus of the users, a lot of wireless sensor network localization algorithms have been proposed in the recent twenty years [2]. These localization algorithms can be divided into two categories according to the distance acquisition process, i.e., range-based algorithms and range-free algorithms. Table 1 shows four main indicators of a range-base and range-free algorithms, and the corresponding affecter. In another way, these localization algorithms can be classified as distributed algorithms or centralize algorithms based on their working mode. Table 2 shows the same four indicators and also lists the corresponding affecter of centralized and distributed algorithms, respectively.

Table 1. The comparison of the range-based and range-free algorithms

	Range-based	Range-free
Accuracy	Ranging algorithm	Geometric algorithm
Energy consumption	Signal transition	Instruction execution
Coverage area	Signal cover	Network topology
Costs	Ranging module	Execution module

Table 2. The comparison of the centralized and distributed working mode

	Centralized mode	Distributed mode
Accuracy	Data collection	Position merging
Energy consumption	Signal transition	Position merging
Coverage area	Network topology	Anchor deployment
Costs	Central module	Anchor equipment

The comparisons in Table 1 and Table 2 present the differences of algorithms clearly. Range-based localization algorithms need to acquire the distances of nodes, and the working principle is relatively concise. RSS-profiling [3, 5], AOA [4] and TDOA [5] are the most currently used techniques which use geometrical and physical principles to ensure the accuracy of positioning. Its disadvantage lies in that the sensor nodes must be equipped with a related hardware. However, the function of received signal strength identification had gained ground quite with the ceaselessly-risen standard of hardware. Range-free localization algorithms come from the research of nodes geometry relationship and the analysis of network topology. Although this kind of algorithms has the advantage that they can work without the ranging module, they are susceptible to accumulative error. Centralized localization algorithms are the most logical method and the centralized mode simplifies the tasks of the sensor nodes greatly. But in a large-scale wireless sensor network, centralized mode may cause much more energy consumption. Distributed localization algorithms are more difficult to design since the complex process of position merging.

The rest of the paper is organized as follows. Section 2 discusses the related localization schemes using MDS algorithm. Section 3 introduces the proposed MDS-MAP(LF) from the aspect of local nodes positing, where the optimum principle is explained and a corresponding simulation is given. Section 4 introduces the proposed MDS-MAP(LF) from the aspect of global map merging. It shows the importance of cluster expansion. Section 5 provides the simulation results of MDS-MAP(LF) and analyzes the comparison to existing method. Finally, section 6 concludes the paper.

2. Related Work

Many localization algorithms have been proposed to locate nodes in wireless sensor networks and describe the use of MDS. Shang et al. [6] proposed MDS-MAP algorithm which uses classical MDS to generate the map nodes used in WSN, and this algorithm was further extended to MDS-MAP(P) [7]. MDS-MAP(D) [8] is an improved method of MDS-MAP(P), it shows a better positioning accuracy by using sensor nodes cluster. Shon et al. [9][10] also proposed cluster-based MDS localization schemes in wireless sensor networks, which typically represent the distributed MDS-MAP approach. Each cluster of the sensor nodes builds the local map using classical MDS algorithm, and then clusters will conduct local map fusion process to shape the entire network location map. The main drawback of these algorithms is that if there are many disjoint clusters exist in the system, then, it will be impossible to map local coordinate system into global coordinate system.

Chen et al. [11] proposed a localization algorithm based on MDS using classified RSSI, it is concluded that the error in the shortest path based distance estimation is high which leads to high localization error. It provides a better accuracy by giving weight to each communication path according to RSSI. However, it still has relatively large estimate error once the sensor nodes lie in the big error area that defined in section 3. Also concerning about the obvious error caused by shortest path algorithms, [12] proposed an improved MDS-based algorithm for localization in WSN, where the distance matrix error is decreased by applying heuristic approach under some ideal assumptions.

Through study and comparison of various positioning schemes in wireless sensor networks, this paper proposed a novel localization method MDS-MAP(LF), it shows a better accuracy in local maps and a better convergence in the process of building global map. The proposed method MDS-MAP(LF) leverages low frequency signal for the inter-sensor distance measure, which improved the small local maps accuracy by realizing the two-hop distance better calculated and enhanced the probability of inter-cluster mergence.

3. Local Positioning with MDS-MAP(LF)

3.1. Local Positioning Error Analysis of Classical MDS-MAP

Classical MDS-MAP belongs to the centralized algorithms, which has range-based and range-free modes. In the algorithm, the shortest paths between each pairs of sensor nodes are firstly acquired by RSSI in the range-based mode or number of hops in the range-free mode. These data will be used to construct a global distance matrix for MDS, which is prone to error accumulation. In order to enhance the accuracy of the positioning result, researchers proposed distributed MDS-MAP algorithms, which conduct several classical or improved MDS-MAP algorithms in a local small area. Local maps are then merged together by their common nodes.

It is evident that these algorithms can achieve better accuracy in the uniformly distributed or connectivity well circumstances. However, if the network is sparse or located in an extreme scenario, the accuracy will decline quickly. It is pointed out in [13] that since classical MDS-MAP uses the length of the shortest path such as the Euclidian distance between nodes, classical method is sensitive to the shape of the network. They presented MDS-MAP(I) and demonstrated its accuracy by means of different linear transformations.

Although MDS-MAP(I)can enhance the positioning accuracy, it is complex in the data calculation process. Here we analyze the shortest path acquisition process in MDS-MAP algorithms and show how errors come. Positioning methods using MDS algorithm usually collect shortest path by Dijkstra or Floyd algorithm, which are not designed for wireless but wired networks. So they perform better in a regular network, but will fail or show big mistakes in a large random distributed network easily. For example, in Figures 1 and 2, three wireless sensor nodes are noted as A, B and C. Each node's communication radius is 15, and node A has a neighbor B, node B has two neighbors A and C. The distance between neighbor nodes could be acquired precisely by RSS profiling technique.

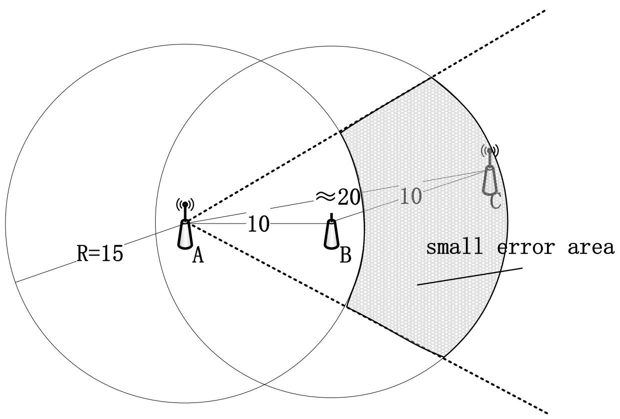

Fig. 1. Wireless sensor node C belongs to a small error area, the estimated distance between node A and node C is relatively accurate

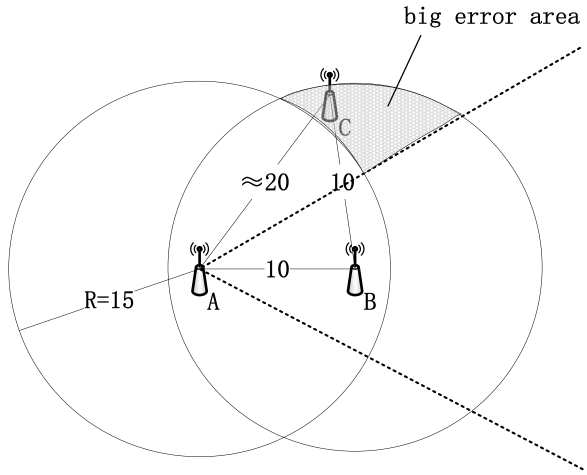

Fig. 2 Wireless sensor node C belongs to a big error area, the estimated distance between node A and node C is relatively crude

When positioning sensor nodes A, B and C using MDS algorithm, the shortest path between sensor nodes A and C will be estimated by hops since no direct communication exists. If sensor node C belongs to the grey small error area of Figure 1, the estimated shortest path between node A and node C is relatively accurate, but once sensor node C is in the grey big error area shown in Figure 2, the corresponding estimated distance is crude.

In the MDS-MAP algorithms, positioning error of the local area is extremely easy to cause an error accumulation, and this will further limits the final positioning accuracy of the algorithms. Therefore, this paper proposes a range-based method MDS-MAP(LF), which utilizes low frequency signal during the local positioning process. Given the better transmission features of low frequency signal, MDS-MAP(LF) improves the accuracy of local maps. It is based on the realization of two-hop distance valid identification at the same receiving sensitivity, which provides higher accuracy than shortest path algorithms.

3.2. Link Feature of Low-Frequency Signal

In a wireless communication environment, the relationship between received signal strength and distance can be obtained as Friis formula [14], which describes the propagation of a radio signal in free space:

$$P_r(R) = \frac{P_t G_t G_r \lambda^2}{(4\pi R)^2 L} \quad (1)$$

where $P_r(R)$, R, and P_t denote the received signal strength at the position, meters from the emission point, and the transmitted power, respectively; G_t and G_r indicate the transmission and reception gain, respectively. Paper [15] gives a further simulation to show the relationship between antenna characteristics and sensor network performance. Letter λ denotes the wavelength of the radio signal and letter L indicates the system loss factor. It shows that, every ten fold decrease in the frequency (also means tenfold increase in the wavelength) of a signal means an increase by 20 dBm in received signal strength. According to the widely used Shadowing link loss model [16, 17, 18], the simplified formula gives a way to estimate the received signal strength:

$$P_r(R)_{dBm} = A - 10\eta \times \log_{10} R \quad (2)$$

where $P_r(R)_{dBm}$ denotes the received signal strength at the position, and R is the meter from the emission point, and the unit of power is dBm. Letter A indicates the received signal strength at the position which is one meter from the emission point, and η denotes the path loss factor, which is decided by the actual communication environment. Most currently used wireless sensor nodes or chips, such as the CC24 series and the CC25 series radio transceiver produced by TI Company, work at the 2.4GHz and its transmitted power is usually around 10dBm. The receiving sensitivity of sensor nodes can come to -90dBm.

Here Figure 3 gives a simple simulation to the attenuation of signal intensity using the Shadowing link loss model. We assume the wireless sensor nodes equipped the chip mentioned above and the communication environment is poor by setting η to 3.5. The frequencies of the radio signal are 2.4GHz and 800MHz. It shows that the higher frequency the radio signal uses, the faster it fades. Figure 4 gives a better explanation of the two kinds of wireless sensor nodes communication coverage, it shows that, with the same transmitted power and receiving sensitivity, radio signal at the frequency of 800MHz has a better transmitted area than the signal at 2.4GHz.When the emission frequency is 2.4GHz, the communication coverage is around 51.801. And as frequency drops to 800MHz, the corresponding coverage is around 97.034.

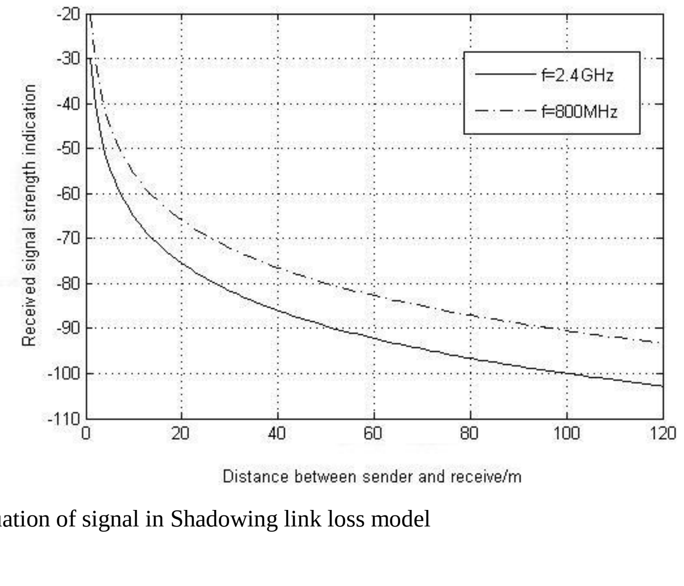

Fig.3. Attenuation of signal in Shadowing link loss model

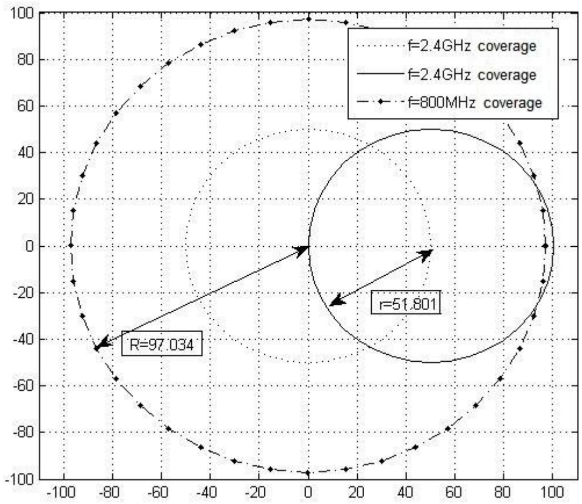

Fig. 4. Communication radius of wireless sensor nodes with different signal frequency

3.3. Building Local Maps with MDS-MAP(LF)

In this subsection, 2-hop clustering are used to build local maps, and each cluster maintains a distance matrix using distance information based on RSSI and the IDs of neighboring nodes received from its own cluster. Table 3 gives a pseudo code running by the cluster head to obtain relative coordinates within a cluster using the MDS algorithm.

Table 3. The pseudo code of MDS-MAP(LF) algorithm in each cluster

Algorithm: MDS-MAP(LF) in each cluster
Input: Information of each node
Output: Member Coordinate

if role = Cluster head
    then m ← Number of cluster member
    for i ← 1 **to** m
        for j ← 1 **to** m
            do Distance Matrix[i][j] ←∞
    for i ← 1 **to** m
            do Distance Matrix[node id][Neighbor Distance[i][j][0]] ← Neighbor Distance[i][j][1]
    ~~Dijkstra(Distance Matrix)~~ **LF-based RSSI**(Distance Matrix)
MDS(Distance Matrix, Member coordinate)
return Member Coordinate

When cluster head performs code from line 1 to line 5, it sets the initial distance between all pairs of nodes to infinite since cluster head received no neighbor distance message. After the preparatory job for building a distance matrix is completed, the cluster head conducts code from line 6 and line 7 to refresh the distance matrix according to the neighbor distance message it received. In line 8, instead of using the shortest path algorithm such as Dijkstra, the MDS-MAP(LF) acquires the 2-hop distance by leveraging the better coverage of low frequency positioning signal. This fills the gap in the distance matrix with a higher accuracy. Then the line 10 is performed to use the MDS algorithm and it results in relative coordinates of all sensor nodes during a cluster. The simulation results of both Dijkstra-based MDS-MAP(D) and LF-based MDS-MAP(LF) are shown in the simulation and result analysis section.

4. Local Position Merging Using MDS-MAP(LF)

4.1. Merging Principle and Cluster Expansion

After the establishment of the local maps, wireless sensor network will merge these local clues to build a larger or global map. In this procedure, small local maps can also change their relative coordinates into absolute coordinates when the cluster find an anchor node. The anchor nodes distributed randomly or uniformly can obtain their absolute coordinates precisely by given more resources. In consideration of cost, the amount of anchor nodes should be as small as possible, but this will postpone the convergence rate of global map establishment. One way to solve this problem is to treat the wireless sensor nodes which have changed their relative coordinates into absolute coordinates as new anchors. Therefore these new anchors will provide coordinate information to other sensor nodes.

In order to reduce the redundant traffic between sensor nodes, wireless sensor network often takes the cluster as communication unit rather than the single node. Wireless sensor nodes will join in several clusters before they conduct some application such as building global map [19, 20]. In MDS-MAP(D) algorithm, each cluster builds its local map and tries to change the relative coordinates into absolute coordinates by utilizing common nodes between adjacent clusters. Figure 5 explains the condition of mergence, and depicts the advantage of MDS-MAP(LF) algorithm in this process. It is assumed than cluster A and cluster B are neighbors using MDS-MAP(D) algorithm, sensor nodes a and b are their common nodes and sensor nodes c and x belong to cluster A only. Dotted line L1 is determined by the node a and node b, L2 and L3 are two perpendicular lines of L1. It is obviously that cluster A and B cannot merge together since there are only two common nodes between them. Some of the nodes, such like node x, cannot be located by cluster B since it will find two possible coordinates for sensor node x, which are the real position and mirror position x’. By using MDS-MAP(LF) algorithm, sensor node communication coverage can be expanded and the corresponding cluster will have more sensor nodes compared to MDS-MAP(D). For example, cluster B can expand to cluster B*, which includes sensor node c. The common nodes between cluster A and cluster B* can make a mergence by eliminating the mirror position x’ using c’.

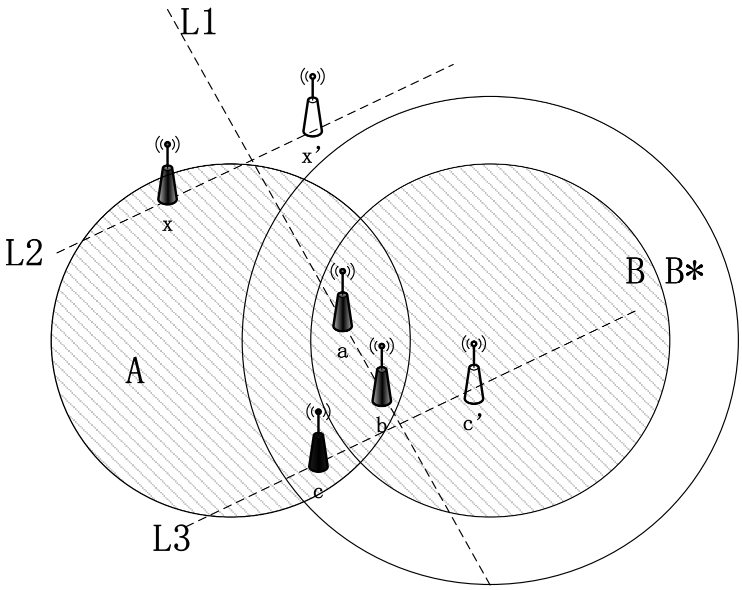

Fig. 5. Condition of a mergence between two adjacent local maps and effect of cluster expansion

Figure 5 shows that cluster expansion, realized by MDS-MAP(LF) algorithm, can make the unification of two neighbor clusters more easier [21], this kind of expansion will also affects the process of building global map. Besides the positioning accuracy, convergence rate is an important standard for distributed MDS-MAP algorithms. The fast and complete mergence is the basic of convergence. In a large scale wireless sensor network, two neighbor clusters or domains will choose a new direction respectively for local position fusion once they cannot be stitched together. They need to wait until there are at least three common nodes available. In a homogeneous wireless sensor network, the waiting time can be very short and hardly cause a convergence fail or a big positioning error. But two neighbor clusters in an inhomogeneous wireless sensor network may fail to merge together as shown in Figure 6, which gives a depiction to the process of cluster fusion. In Figure 6, Clusters are denoted by a circle with a capital letter, and there is a line between them if two clusters have at least one common node. The number of the line shows the actual amount of common nodes. Figure 6(a) is the initial state of the inhomogeneous wireless sensor network, which have eight clusters. Each cluster builds its own local map and finds its neighbor clusters with the MDS-MAP(D) algorithm. It is assumed that cluster A is the first cluster to conduct a mergence. Cluster A will choose cluster E since it is the only available direction by the constraint condition mentioned above, and they will merge into a new cluster S1 shown by Figure 6(b).With the same constraint condition, Figure 6(c) shows a fusion of clusters S1, D and H, and this leads to a growth of common nodes with cluster B. Finally in Figure 6(d), every cluster arrives to a stable state, and cluster A is included in cluster S3. That means cluster A cannot build a global map since there are clusters C and F outside the mergence, and the result will be the same when we choose the other clusters as the beginning point.

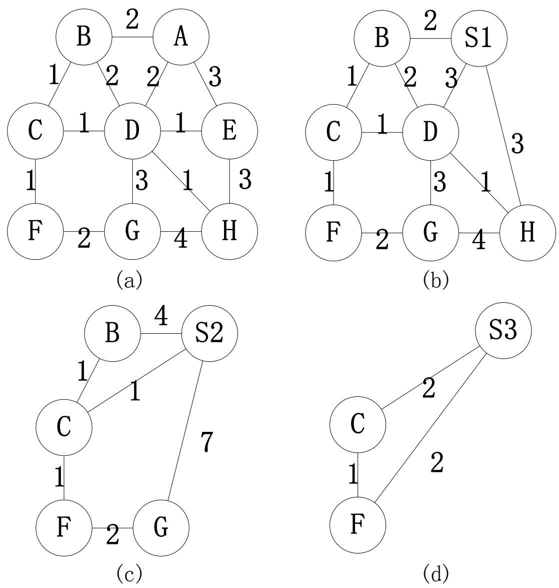

Fig.6. The global map building process of an inhomogeneous wireless sensor network

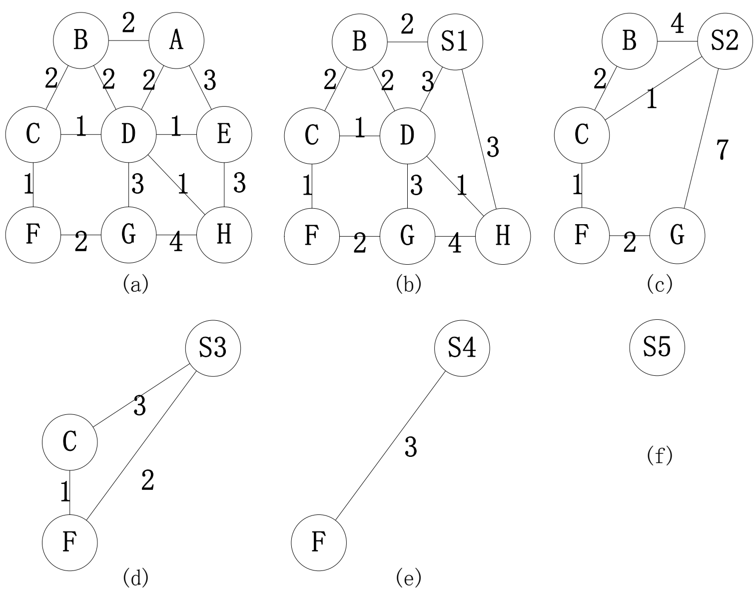

Fig.7. The global map building process of an inhomogeneous wireless sensor network after a cluster expansion

At the process of building local map using MDS-MAP(LF), wireless sensor nodes will have a better vision to seek for their neighbors and this can influence the area of the clusters. This kind of cluster expansion will also be useful to improve the mergence between clusters. Figure 7 gives an example of the effect in the same network with Figure 6, the only difference is the common node amount of cluster B and cluster C, which comes to two. We also choose cluster A as the start point in Figure 7(a), the following steps Figure 7(b) and Figure7(c) are quite same with the corresponding steps in Figure6. When cluster S3 begins to diffusion its area in Figure 7(d), it can find an available direction and keep the mergence going. Finally through Figure 7(e) and Figure 7(f), the cluster S5 will have a global map and the result will be the same when we choose the other clusters as the beginning point.

4.2. Conduct Local Position Merging Using MDS-MAP(LF)

After the local map of a cluster is calculated by the cluster head, each cluster head node begins to contact the neighbor cluster and tries to participate in a possible merging. Table 4 shows the pseudo code for the merging step in MDS-MAP(LF).

Table 4. The pseudo code of MDS-MAP(LF) algorithm

Algorithm: MDS-MAP(LF) in merging phase **Input**: Member Coordinate **Output**: Merged Member Coordinate
01: **while** all neighbor clusters are merged ≠ true
02: **do LF-based cluster expansion**(Distance Matrix)← Member Coordinate
03: **if** role = Cluster head has some unimpeded neighbor clusters
04: **then send** merging phase message **to** neighbor cluster head
05: **send** Member Coordinate **to** all neighbor heads
06: **else if** role = Cluster head has no unimpeded neighbor cluster
07: **do** listen to merging phase message
08: **while** receive merging phase message
09: **do** Calculate the rotation angle and the new coordinate of all cluster nodes
10: **send** new coordinate **to** all cluster nodes
11: **return** Merged Member Coordinate

Using line 1, each cluster decides whether a merging request should be sent to the neighbor cluster. While all neighbor clusters are not merged together, each cluster performs line 2 to expand its coverage and capture more common sensor nodes. It can enhance the possibility of a merging which makes the MDS-MAP(LF) a better convergence. If a cluster head has some unimpeded neighbor clusters, the cluster head performs code from line 3 to line 5. It transmits merging phase message and its member coordinate to the corresponding cluster head to require a local position merging. If a cluster head has no unimpeded neighbor cluster, it uses line 6 and line 7 to hold on the listen mode. Once a cluster head receives a merging phase message it performs line 8 to line 11. Cluster head computes the rotation angle and the new coordinate of all cluster nodes according to the received member coordinate sent by the neighbor cluster. It returns the merged coordinate of all cluster nodes. The influence of LF-based cluster expansion is shown in the simulation and result analysis section.

5. Simulation and Result Analysis

5.1. Local Positioning Accuracy

By using low frequency signal in the process of positioning, wireless sensor nodes will find more neighbors, such as sensor node A could find sensor node C in Figure 1. It will provide more accurate data compared to the estimated result acquired by shortest path algorithms. In order to give a further reflection of accuracy improvement, this paper compares the MDS-MAP(LF)with the distributed MDS-MAP(D), which uses classical MDS algorithms to build the small local maps. We conduct a simulation for the local positioning process of MDS-MAP(D) and MDS-MAP(LF) respectively in Figure 8 and Figure 9.

It is assumed that the communication radius of wireless sensor nodes is 40 meters, and the actual location of the 100 nodes is generated randomly in a 320 meters * 320 meters area, this means the each node should have nearly 5 neighbor nodes by mathematical calculation. Figure 8 shows a local positioning map generated by MDS-MAP(D) algorithm. There are 10 nodes in this local map, and each node's real position is denoted by a solid dot, the corresponding calculated position is mark by an asterisk. Also the positioning errors are shown as the length of the lines which connect the solid dots and the asterisks.

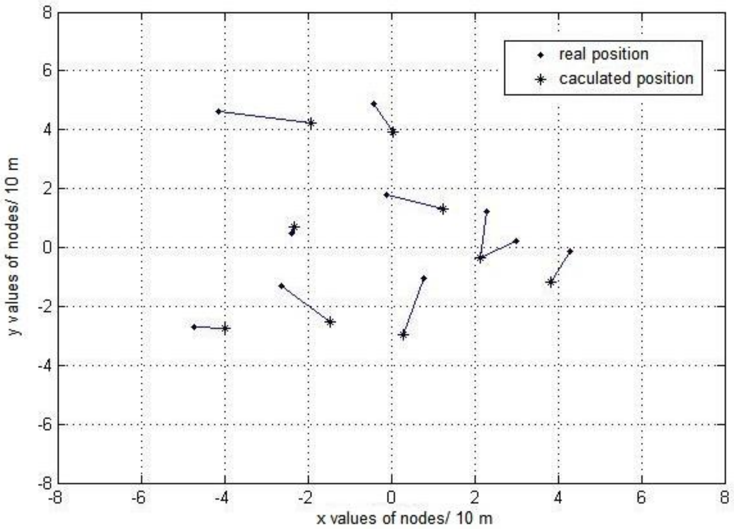

Fig. 8. Local positioning map of 10 sensor nodes acquired by MDS-MAP(D)

With the same assumption, Figure 9 shows the local positioning map of the 10 nodes mentioned above using MDS-MAP(LF). Each real position of the 10 nodes is the same with Figure 8 and also denoted by a solid dot. The corresponding calculated position is mark by an asterisk. Positioning errors are shown as the length of the lines which connect the solid dots and the asterisks. By comparing these two pictures, we can find that, the positioning error of many nodes decreased as the line between the solid dot and asterisk is shorter in Figure 9, this demonstrates a better accuracy of two-hop distance valid identification realized by low frequency signal compared to the estimated value calculated by shortest path algorithms.

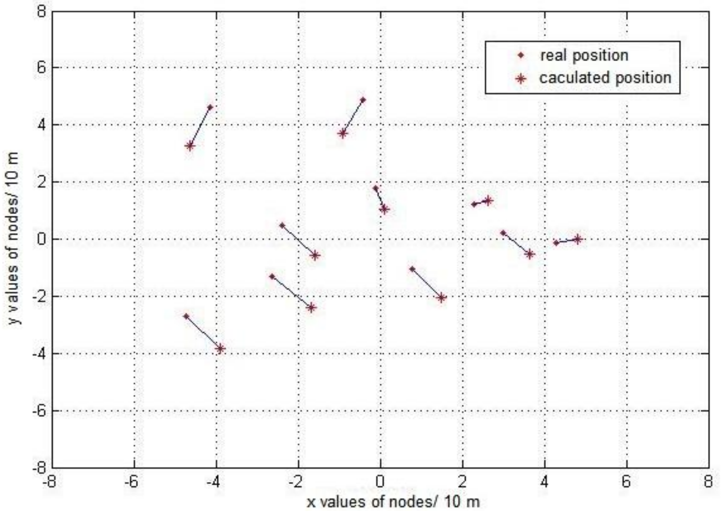

Fig. 9. Local positioning map of 10 sensor nodes acquired by MDS-MAP(LF)

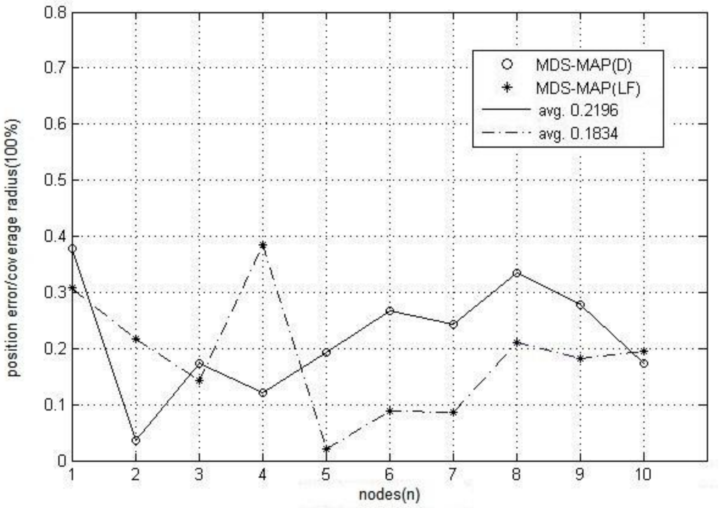

Fig. 10. Comparison of MDS-MAP(D) and MDS-MAP(LF) in term of positioning error

The comparison of MDS-MAP(D) and MDS-MAP(LF) in term of local positioning error is shown in Figure 10. It depicts the percentage of positioning error for each of the 10 sensor nodes mentioned in Figure 8 and Figure 9, and shows the average error of both localization algorithms. Using MDS-MAP(LF), the calculated position is more accurate for most wireless sensor nodes except the nodes 2, 4 and 10. The average error of MDS-MAP(LF) is 18.34%, which is nearly four percentage points lower than the average error of MDS-MAP(D).

5.2. Local Position Merging Probability

Given a better coverage of each cluster, MDS-MAP(LF) performs a higher merging probability based on the mathematical derivation. Based on this analysis, Figure 11 shows the successful merging probability of any adjacent clusters in some relatively low connectivity scenarios.

While the node connectivity is 5, the merging probability of MDS-MAP(D) shown as the grey rectangle is just 31.88%, and the corresponding value of MDS-MAP(LF) shown as the black rectangle is 47.83%. And while the node connectivity comes to 10, each algorithm performs a bigger merging probability. The MDS-MAP(D) shows 84.62% and the MDS-MAP(LF) shows 95.42%. This suggests that the lower node connectivity the wireless sensor network is given, the smaller merging probability a cluster acquired. It also indicates that the influence of cluster expansion proposed by MDS-MAP(LF) is more remarkable in a sparse wireless sensor network. By enhancing the merging probability of adjacent clusters, MDS-MAP(LF) performs a better convergence during the local position merging process.

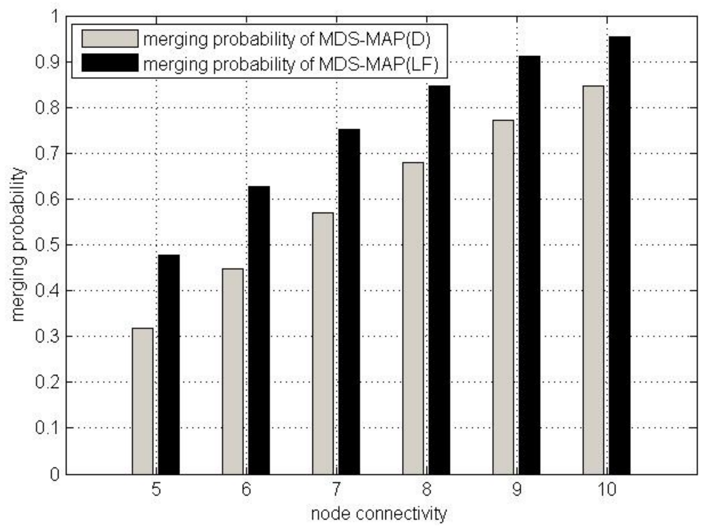

Fig. 11. Comparison of MDS-MAP(D) and MDS-MAP(LF) in term of merging probability

6. Conclusion

The positioning error of distributed MDS-MAP algorithms comes from two aspects: the local positioning error and the position merging error. The cause of local positioning error is the crude two-hop distance estimated by the shortest path algorithms, which are not designed for wireless but wired networks. The convergence process of local clusters can lead to a large position merging error, especially in the inhomogeneous network. This paper proposed a novel MDS-MAP(LF) algorithm, which uses low frequency signal for the inter-sensor distance measure rather than shortest path algorithms. The simulation result shows that the accuracy of local positioning map has increased by more than 3% comparing with the distributed MDS-MAP algorithm. In terms of global map building process, MDS-MAP(LF) algorithm gives a better vision to local clusters, which improves the complete convergence probability. The future work should be focused on an improved algorithm of cluster expansion, which may achieve the function of abnormal nodes localization and exclusion.

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